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An Investigation into the Airflow Through Pipe Organ Pallet Valve Openings Using Particle Imaging Velocimetry

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Summary

Many organists believe that they can control the transients of the pipe speech on pipe organs with mechanical key action by the way in which they move the keys. As organs get larger the actions also have higher inertia and have to control a greater airflow. The defining characteristic of mechanical pipe organ actions is pluck. This is felt as an initial resistance as the key is depressed due to the pressure difference across the pallet valve under the pipes, which reduces as soon as the pallet starts to open. Due to the need to keep the key force within comfortable limits inertia has to be minimised which means that action components connecting the key and pallet cannot be entirely rigid which causes them to behave like a spring. This results in a degree of movement of the key until sufficient energy is stored to overcome pluck at which point the pallet starts to open and catches up with the key. In order to maximise the possible degree of control of the opening of the pallet, pluck has to be minimised. This project uses Particle Image Velocimetry to study how variations in the design of the pallet valve affect its efficiency and also how the traditional materials used to face the pallet affect airflow.

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1. Introduction

The most common design of windchest used in pipe organs, particularly those with purely mechanical (tracker) action has remained essentially unchanged for several centuries. It is illustrated in Fig 1. It is called the bar and slider chest because a bar (or groove) connects all pipes playing the same note and sliders (S) turn individual ranks of pipes on and off.

The Pallet box, ABDH, contains compressed air at, typically, 500Pa to 1kPa (50mm to 100mm water, being the standard unit of pressure used by organbuilders). When the pipes are not sounding, the groove is at atmospheric pressure.

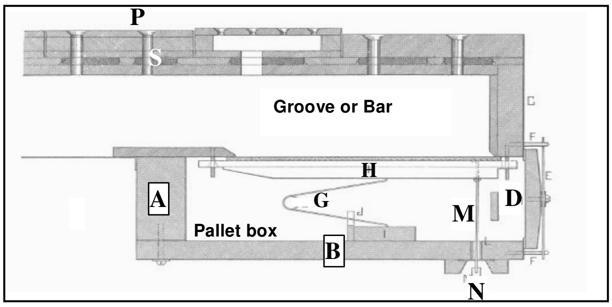

Fig 1. Cross section of Bar and Slider windchest. Pressurised air in pallet box ABDH, atmospheric pressure in groove until pallet, H, opens downwards. Net force against bottom of pallet when closed. Audsley, George Ashdown. *The Art of Organ Building* (Mineola, Dover 1965 republication of 1905 edition, Dodd, Mead & Co) Fig CLIX, adapted

The pipe feet are placed in the conical holes P and the pipes that sound when a key is depressed are selected using the sliders S that move perpendicular to the plane of the diagram. There is one groove for each key. The keys are attached by a system of mechanical links to the point N. When the keys are at rest, the air is prevented from reaching the pipes by the pallet H, which is hinged at the left side. It is rectangular and covers a rectangular hole and is faced with either leather or a layer of felt covered with leather in order to improve the seal. It is held closed by a force which is the sum of the force exerted by the spring G and the force due to the excess pressure inside the pallet box. When the key is depressed, the tracker M is pulled down, which in turn pulls down the pallet. As soon as the pallet starts to open, the air pressures in the pallet box and groove start to equalise and the force against the bottom of the pallet reduces. Thus a greater force is required to start the key moving than to keep it depressed. This initial resistance is called pluck because it feels like the resistance felt at a harpsichord key as the quill plucks the string. The magnitude of the pluck is determined by the area of the rectangular opening between the pallet box and the groove and it is also found empirically to depend on the rate of flow through the pallet valve. Increasing the size of the pallet opening in order to increase the airflow to pipes results in a greater pluck, which can become excessive in larger organs. This project looks at how different pallet facings affect the airflow at constant degrees of pallet opening in order to understand how it might be possible to optimise the airflow to pluck ratio.

2. The model

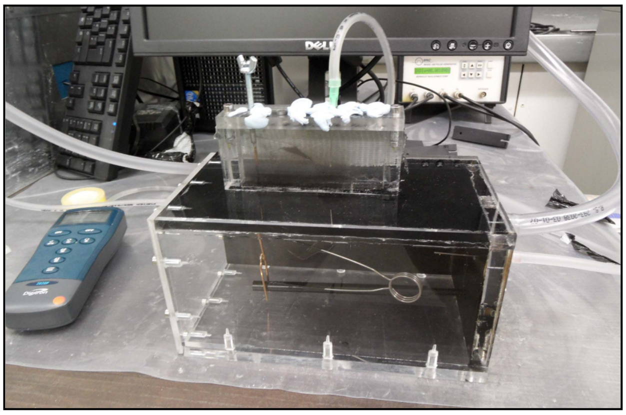

Fig 2. The model windchest. Air inlet at right. Pallet drop adjustment via the screw at the top.

Organ windchests are traditionally made from wood, but for ease of construction and to make the model transparent, Perspex was used. In general, organs are custom made for each location and organbuilders develop their own preferred details of construction. The model does not represent any particular instrument and the pallet box is only wide enough to supply one groove rather than the whole compass of a full size organ. The pallet opening is 70mm by 10mm. The pallet face is 89mm by 21.5mm and the pivot point is 15mm outside the pallet opening. The pallet drop is measured 6mm from the open end of the pallet opening. A pallet of this size would open by between about 5 and 7mm in a typical organ. The pallet box is 200mm long, 100mm wide and 90mm deep. The groove is 100mm long, 10mm wide and 45mm deep.

Pressures in the pallet box and groove were measured with Digitron digital manometers and the flow was measured with a Key Instruments FR4500-4A70 acrylic block flowmeter. The pallet box pressures used were 500Pa and 1kPa as these correspond to 50 and 100mm water which is the range of pressures typically used in mechanical action organs. As measurements were taken at fixed pallet drops and therefore fixed flow rates, a constant flow air supply was used rather than a standard organ blowing system which supplies constant pressure. The pressure in the pallet box was maintained at the required pressure by adjusting the flow rate.

The pallet facings used were plain Perspex, pallet leather and pallet felt covered with pallet leather. The felt and leather were supplied by an organ component supplier and are intended for this purpose. When installed in the model, the leather had a thickness of 1.0mm and the felt/leather a thickness of 3.6mm. The coverings extended over the whole surface of the pallet. Discussion with organ builders suggested that a layer of felt between the pallet and the leather reduces the perceived magnitude of the pluck by reducing the initial flow rate at the expense of slowing the initial pressure rise time. It is virtually impossible to eliminate leaks into the groove round a closed pallet, and pipe organs invariably incorporate some means of venting this airflow in order to prevent it from causing the pipes to sound.

The position of the pallet is determined by a threaded rod with a pitch of 0.7mm passing through the top of the groove. This is not the standard mechanism for opening pallets but is necessary in order to avoid any shadows when the pallet is illuminated for PIV work.

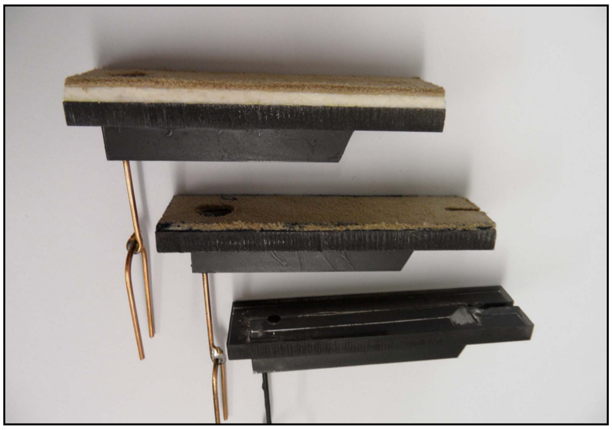

Fig 3 The three pallet facings. Top: felt (white) plus leather, middle: leather, bottom: no facing

Plain circular holes of 6 and 10mm diameter were used in place of pipes as these are representative of the areas of the toe holes of organ pipes.

Fig 4. The felted and leathered pallet installed in the pallet box. The pallet is held open by the rod visible just above the middle of the front of the pallet and passing through the pallet opening.

3. Results

Measurements were made using each of the two holes, 6 and 10mm diameter, at each of the two pressures, 0.5 and 1kPA. The pressure in the groove and the flow through the system were measured, with the resistance of the pallet opening calculated from these by dividing the pressure drop across the pallet by the flow rate. Flow rates are unreliable at flow rates of less than $5x10^{-5}m^3s^{-1}$ due to the operating range of the flowmeter. The graphs show measurements for 0.5kPa pallet box pressure and a 6mm diameter hole:

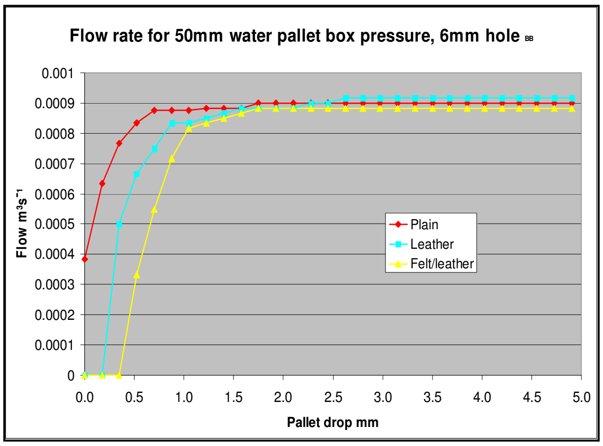

Fig 5 Graph showing airflow against pallet opening for the model windchest using a pressure of 0.5kPa and a 6mm diameter hole in place of a pipe.

Fig 5 shows the airflow plotted against pallet opening. All three pallet facings result in maximum airflow at around the same point – 2.5mm pallet drop. There is a clear variation in flow at small pallet drops, with the unfaced pallet showing a significant leak. Airflow past the leather faced pallet does not become measurable until it has dropped by 0.175mm and for the felt and leather covering 0.350mm. The peak airflow is reached at around 2mm movement and 90% of peak airflow is reached between 0.4 and 1.0mm pallet travel but with a delay in the start of the airflow with the faced pallets. Thus the airflow reaches a maximum near the beginning of the key movement, and any further movement will have no significant effect.

There is a discontinuity in the curves just before the peak. This has been observed by other researchers and will be investigated further[1].

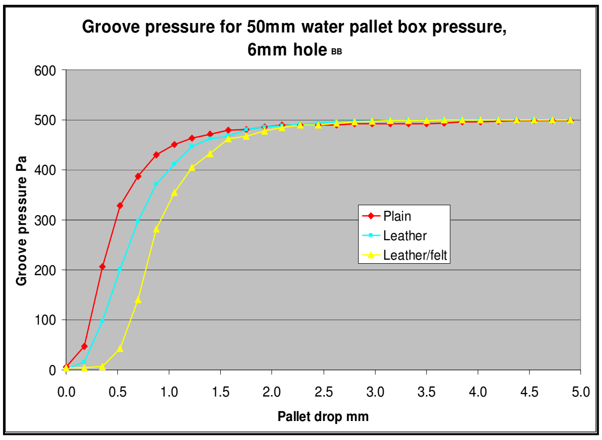

Fig 6 Graph showing groove pressure against pallet opening for the model windchest using a pressure of 0.5kPa and a 6mm diameter hole in place of a pipe

Fig 6 confirms that the pressure in the groove reaches a peak equal to the pressure in the pallet box at the same point as the flow maximises which is at about 2.5mm pallet drop. Fig 6 also shows that the initial pressure rise is slower for the faced pallets.

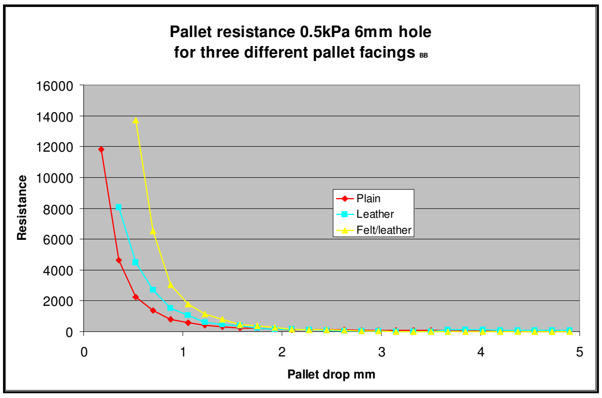

Fig 7 Graph showing resistance of the pallet opening against size of pallet opening for the model windchest using a pressure of 0.5kPa and a 6mm diameter hole in place of a pipe

Fig 7 shows the resistance of the pallet opening, which reduces quickly from a very high value when the pallet is open a small amount.

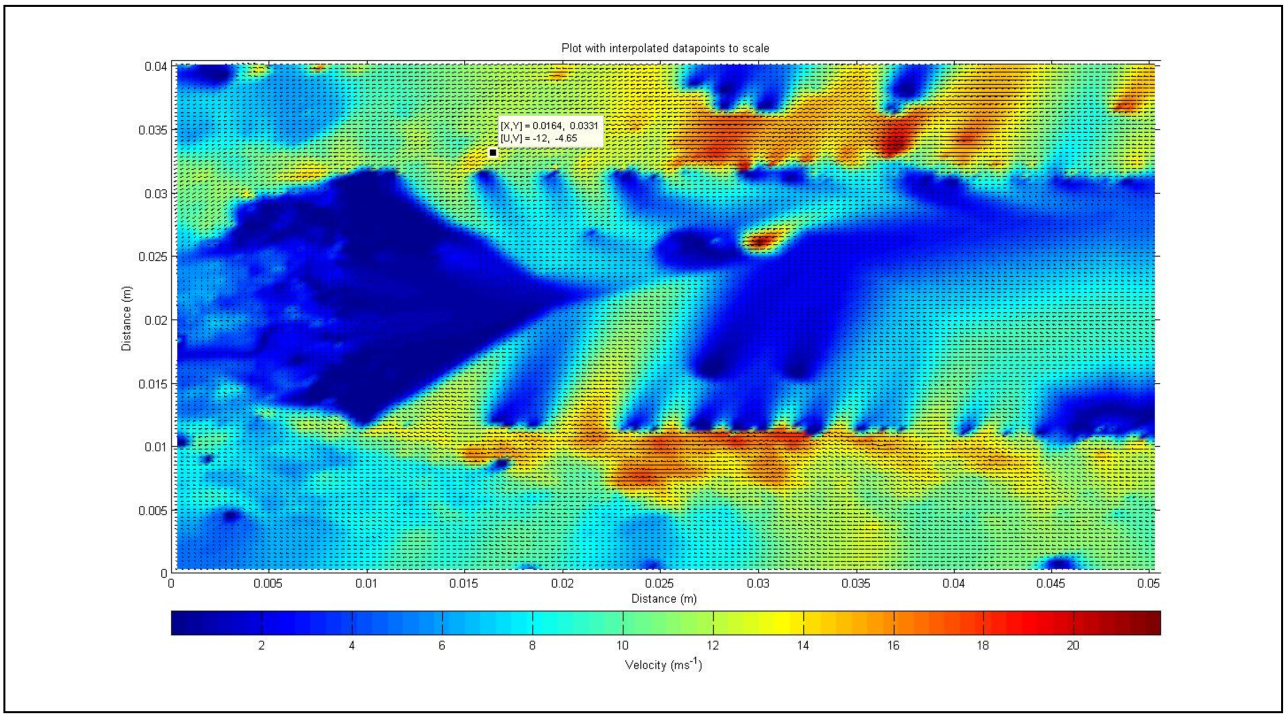

Fig 8 PIV image of airflow round pallet. The open end is to the left. The colours show the magnitude of the flow and the arrows show the direction.

Measurements at the other values of pressure (1kPa) and hole size (10mm) produced similar results.

4. Particle Imaging Velocimetry

The airflow past the pallet has been investigated further using Particle Imaging Velocimetry in order to determine the distribution of airflow. This technique involves injecting small particles into the airflow and taking two photographs illuminated with two short and very intense laser pulses. The movement of the particles is tracked by calculating the cross-correlation function for defined interrogation areas in the photographs and a map of the velocities produced. An example is shown in Fig 8. which shows the underside of the pallet, which is open at the left hand side to a drop of 1.4mm. The colour shows the velocity magnitude of the airflow. Arrows (although not clearly visible at this scale) represent the vector velocity in the (horizontal) measurement plane.

The image in Fig 8 only shows the open end of the pallet which is displaced outwards from the plane of the image. It shows that the maximum speed of flow occurs towards the middle of the image. The flag shows the coordinates of the interrogation area marked with the black square and that the velocity in the x-direction towards the left of the image is $12.00ms^{-1}$ and in the y-direction towards the bottom of the picture is $4.65ms^{-1}$.

The average speed of flow in towards the sides of the pallet is around 2.5 to $3.0ms^{-1}$ reducing towards the right hand side where the opening narrows. For the opening and pressure used in obtaining Fig 8, the flow measured by the flow meter was $0.0022m^3s^{-1}$. This equates to an area of airflow of $7.5x10^{-4}m^2$ whereas a simple geometric calculation of the open area round the pallet gives a maximum area of flow of $1.5\ x10^{-4}\ m^2$. This difference may be attributable to airflow with a velocity component directed into the pallet opening that is not identified in the two dimensional image

5. Conclusions

The leather or felt and leather facings used on pipe organ pallets have traditionally been used to improve the seal of the closed pallet to reduce leakage. They also reduce the airflow past the pallet at small static pallet openings compared with unfaced pallets. This may be due to the facing compressing at the hinged and reducing the area of the pallet opening that is uncovered. There is no effect on the airflow beyond a certain point in the pallets travel and there is no advantage in opening the pallet any further for a given airflow. Ongoing work is investigating the effects at very small openings further.

It has been suggested that the felt and leather combination deforms during opening so that only part of the pallet opening is initially uncovered and thus reducing the magnitude of pluck but spreading its effect over a greater key movement[2]. This is being investigated further.

The existing model has been designed to facilitate the viewing of the airflow in the plane of the pallet opening. A further part of the project will use PIV to investigate whether the design of the pallet hinge results in an uneven deformation of the leather and felt/leather facings particularly at the hinged end. Further models will be used to investigate flow in other planes.

Acknowledgement

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[2] D. Wylde, Henry Willis and Sons. Discussion with author